Decoherence in BEC

D.D., J. Dziarmaga and W. Zurek (Los Alamos)

First generation of BEC experiments

Non-linear excitations, superfluid dynamics, vortices can be described in a mean field approximation (GPE)

$$\Psi(\mathbf{x}_1, \ldots, \mathbf{x}_N) = \prod_{i=1}^{N} \phi(\mathbf{x}_i)$$

$$i\hbar \frac{\partial \phi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \phi + V(\mathbf{x})\phi + g|\phi|^2 \phi$$

Second generation of BEC experiments (already under way)

Explore new physics, **beyond mean-field theory**

- ◇ Schrödinger cat states
- ◇ number squeezed states
- ◇ quantum phase transitions
- ◇ quantum information

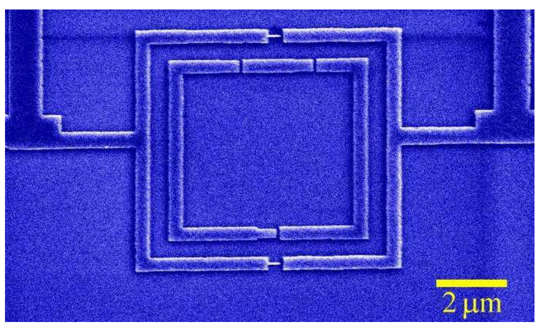
Microscopic quantum superpositions

- ◇ Cavity QED: 2 photons (M. Brune *et al*, PRL **77**, 4887 (1996)).
- ◇ Ion traps: 4 ions (C. Myatt *et al*, Nature **403**, 269 (2000)).

Macroscopic quantum superpositions

- ◇ Detection of a big cat ($N \approx 10^9$ Cooper pairs) in a rf-SQUID. (Friedman et al, Nature **406**, 43 (2000); van der Wal et al, Science **290**, 773 (2000).

Particular persistent-current superposition states were produced, that are eigenstates of the system Hamiltonian



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|L\rangle \pm |R\rangle)$$

$\diamond$ Possible cat states in BEC ($N \approx 10^3 - 10^6$)

– Atomic cats (internal hyperfine levels or double well potential) (Cirac et al, PRA **57**, 1208 (1998); Gordon et al, PRA **59**, 4623 (1998); Ho et al, cond-mat/0011095)

$$H_{\rm int} \propto \Psi_A^\dagger \Psi_B + \text{c.c.}$$

$$\boxed{|\Psi\rangle = \alpha|N,0\rangle + \beta|0,N\rangle}$$

– Atomic-molecular cats (photoassociation or Feshbach resonance) (Casalmiglia et al, PRL **87**, 160403 (2001))

$$H_{\rm int} \propto \Psi_M^\dagger \Psi_{A_1} \Psi_{A_2} + \text{c.c.}$$

$$\boxed{|\Psi\rangle = \alpha|2N_{(\text{atoms})}, 0_{(\text{molecules})}\rangle + \beta|0_{(\text{atoms})}, N_{(\text{molecules})}\rangle}$$

Atomic cats: Two mode approx. $\Psi = \phi_a(x)a + \phi_b(x)b$

$$H = \epsilon_g(a^\dagger a + b^\dagger b) + \frac{u}{2}(a^\dagger a^\dagger aa + b^\dagger b^\dagger bb) + v(a^\dagger ab^\dagger b) - \lambda(a^\dagger b + b^\dagger a)$$

where u and v are two-body interactions, and λ is the Josephson coupling.

When $u - v < 0$ (attractive interactions) and $N|u - v| \gg \lambda$, then the lowest energy subspace contains two macroscopic superpositions

$$\begin{aligned} |\pm\rangle &= \frac{1}{\sqrt{2N!}}[(a^\dagger)^N \pm (b^\dagger)^N]|0\rangle = \frac{1}{\sqrt{2}}(|N,0\rangle \pm |0,N\rangle) \\ &\neq \frac{1}{\sqrt{2N!}}(a^\dagger \pm b^\dagger)^N|0\rangle \end{aligned}$$

Preparation of the cat state: Start with all atoms in state A, apply a strong light pulse to produce an atomic coherent state of A and B with relative phase $\phi = 0$. Then turn on the Josephson coupling for some appropriate time, then turn it off. The final state is a Schrödinger cat state

Does the cat live long enough?

External decoherence due to the thermal cloud

- ◇ two-body inelastic collisions (amplitude decoherence): $O(z^2)$, $z = \exp(\beta\mu)$ is the fugacity.

- ◇ two-body elastic collisions (phase decoherence): $O(z)$. They give the leading contribution to decoherence

Master equation $\frac{d\rho}{dt} \propto [N_A - N_B, [N_A - N_B, \rho]]$

Decoherence rate:

$$\boxed{t_{\text{dec}}^{-1} > 16\pi^2 \left(4\pi a^2 \frac{N_{\text{E}}}{V} v_T\right) N^2}$$

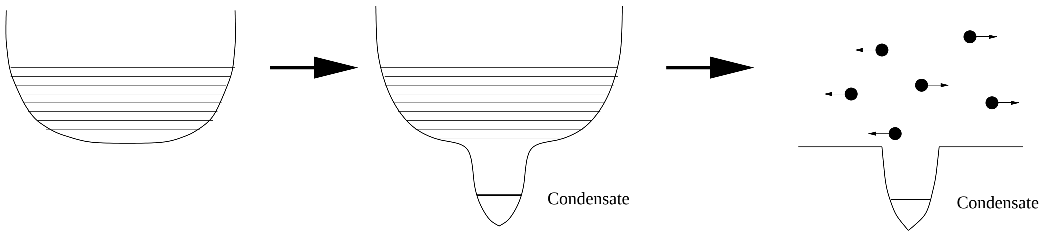
$T = 1\mu\text{K}$, $w = 50\text{Hz}$, $a = 5\text{nm}$, $v_T = 10^{-2}\text{m/s}$, $V = 10^{-15}\text{m}^3$

$$t_{\text{dec}} \approx 10^5 \text{sec}/(\text{N}_\text{E}\text{N}^2)$$

For $N = 10^5$ and $N_{\text{E}} = 10^2$, we get $t_{\text{dec}} \approx 10^{-7}\text{sec}$

What can we do to prevent decoherence?

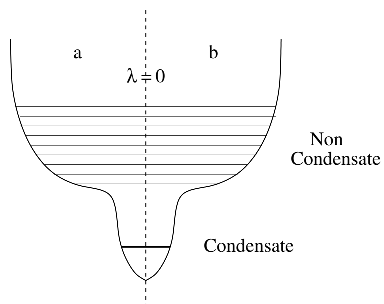
◇ Trap engineering

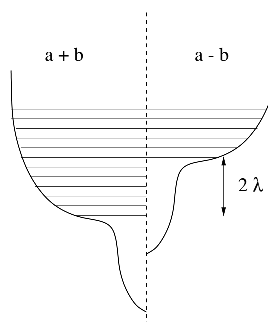


◇ Symmetrization of the environment

$$H_{\mathrm{E}} = \sum_s [\epsilon_s (a_s^\dagger a_s + b_s^\dagger b_s) - \lambda (a_s^\dagger b_s + b_s^\dagger a_s)]$$

$$S_s = \frac{a_s + b_s}{\sqrt{2}}, \qquad O_s = \frac{a_s - b_s}{\sqrt{2}} \rightarrow H_{\mathrm{E}} = \sum_s [(\epsilon_s - \lambda) S_s^\dagger S_s + (\epsilon_s + \lambda) O_s^\dagger O_s]$$





Decoherence-free pointer subspace in BEC

When $2\lambda \gg k_B T$, the antisymmetric environmental states O_s are nearly empty. Only the symmetric states S_s are occupied. These states don't distinguish between A and B.

$\rightarrow$ Collisions involving symmetric thermal states don't destroy the quantum phase coherence of the Schrödinger cat

$$[V, \mathcal{P}_{[\alpha|N,0\rangle+\beta|0,N\rangle]}] = 0$$

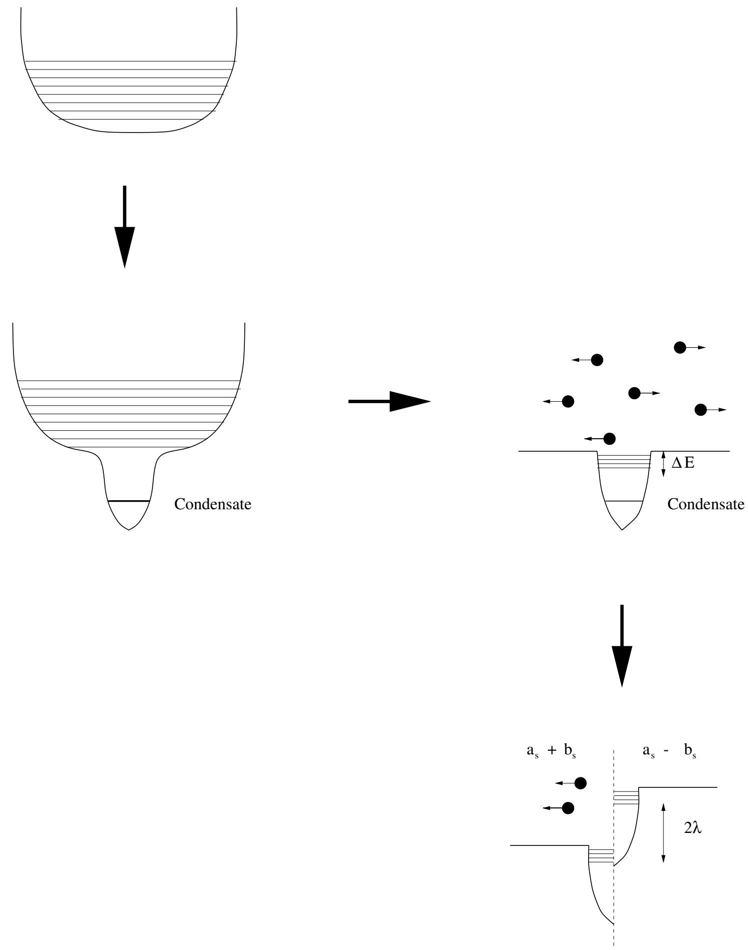
Any superposition $\alpha|N,0\rangle + \beta|0,N\rangle$ is an eigenstate of the interaction Hamiltonian, and will retain its phase coherence. Thus, the subspace spanned by $|N,0\rangle$ and $|0,N\rangle$ is a decoherence free subspace (DFS).

When decoherence matters ...

When the antisymmetric states begin to be occupied, the above commutation relation is only approximate, and the states in the DFS will decohere.

$$t_{\mathrm{dec}}^{-1} > 16\pi^2 \left(4\pi a^2 \frac{N_{\mathrm{E}}^{\mathrm{O}}}{V} v_T\right) N^2$$

where $N_{\mathrm{E}}^{\mathrm{O}}$ is the final number of atoms in the antisymmetric states only



Other sources of decoherence

- ◇ Ambient magnetic fields: use hyperfine levels with the same magnetic moments ($|F, M_F\rangle = |2, 1\rangle, |1, -1\rangle$ of ^{87}Rb).
- ◇ Different scattering rates: typically 1%. Symmetrization can improve decoherence time in two orders of magnitude.
- ◇ Three-body losses: BECs have finite lifetime due to collisions involving three particles. For $N = 10^4$ one atom is lost per second. The loss rate scales as the density squared. Increasing the radius of the dip may decrease the decoherence rate.